New measurement of ϵ'/ϵ by NA48 experiment at CERN

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Plan of the presentation

- Physics motivation
- NA48 as a "Perturbative Expansion" experiment:
  - 1st order: the NA48 "magic" recipe
  - 2nd order: corrections
- Result from 98 and 99 data
- Result including 97 data
- New KTeV result
- World average for $\mathrm{Re}(\varepsilon'/\varepsilon)$
- Conclusions

Physics motivation

Strangeness eigenstates:

$$\mathrm{K}^0(\bar{\mathrm{s}}\mathrm{d}) \quad (S=+1)$$
$$\overline{\mathrm{K}^0}(\mathrm{s}\bar{\mathrm{d}}) \quad (S=-1)$$

CP eigenstates:

$$\mathrm{K}_1 = (\mathrm{K}^0 + \overline{\mathrm{K}^0})/\sqrt{2} \quad (CP=+1)$$
$$\mathrm{K}_2 = (\mathrm{K}^0 - \overline{\mathrm{K}^0})/\sqrt{2} \quad (CP=-1)$$
$$\pi^+\pi^-, \pi^0\pi^0 \quad (CP=+1)$$

Mass and Lifetime eigenstates:

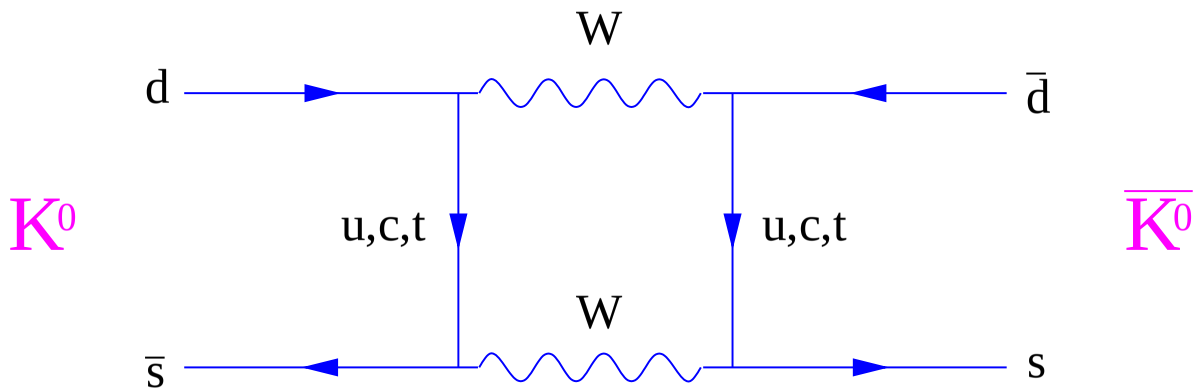
$$\mathrm{K_S} \simeq \mathrm{K}_1 + \varepsilon \mathrm{K}_2 \quad (\mathrm{c}\tau_\mathrm{S} = 2.67 \text{ cm})$$
$$\mathrm{K_L} \simeq \mathrm{K}_2 + \varepsilon \mathrm{K}_1 \quad (\mathrm{c}\tau_\mathrm{L} = 15.5 \text{ m})$$

$\mathrm{K_S}$		$\mathrm{K_L}$	
69 %	$\pi^+\pi^-$	21 %	$3\pi^0$
31 %	$\pi^0\pi^0$	13 %	$\pi^+\pi^-\pi^0$
		27 %	$\pi\mu\nu$
		39 %	$\pi e\nu$
		0.2 %	$\pi^+\pi^-$
		0.1 %	$\pi^0\pi^0$

$$\varepsilon = (2.28 \pm 0.02) \times 10^{-3}$$

Physics motivation, contd.

$\varepsilon \Rightarrow$ Indirect CP violation via $K^0/\overline{K^0}$ mixing



Is there also a component of CP violation in the decay process?

$$K_L = K_2^{-1} + \varepsilon\, K_1^{+1} \qquad \pi^+\pi^-,\ \pi^0\pi^0$$

CP = +1

Need interference of two decay amplitudes

$\pi\pi$ from K^0 can have I=0,2 $\Rightarrow$ amplitudes A_0, A_2

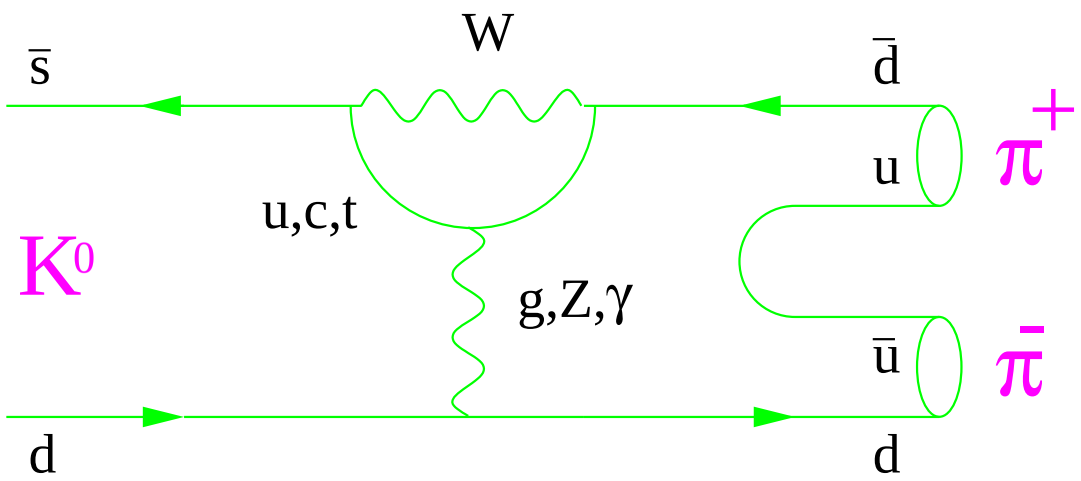
$$A(K^0 \rightarrow \pi\,\pi\,, I) = A_I \exp(i\delta_I)$$

$$A(\overline{K^0} \rightarrow \pi\,\pi\,, I) = A_I^* \exp(i\delta_I)$$

Physics motivation, contd.

$$\varepsilon' = \frac{i}{\sqrt{2}} \mathfrak{Im} \frac{A_2}{A_0} \exp(i(\delta_2 - \delta_0))$$

$\varepsilon' \Rightarrow$ Direct CP violation:



$$\eta_{+-} \equiv \frac{A(\mathrm{K_L} \to \pi^+\pi^-)}{A(\mathrm{K_S} \to \pi^+\pi^-)} \simeq \varepsilon + \varepsilon'$$

$$\eta_{00} \equiv \frac{A(\mathrm{K_L} \to \pi^0\pi^0)}{A(\mathrm{K_S} \to \pi^0\pi^0)} \simeq \varepsilon - 2\,\varepsilon'$$

$$\mathrm{R} = \frac{\frac{\Gamma(\mathrm{K_L} \to \pi^0\pi^0)}{\Gamma(\mathrm{K_S} \to \pi^0\pi^0)}}{\frac{\Gamma(\mathrm{K_L} \to \pi^+\pi^-)}{\Gamma(\mathrm{K_S} \to \pi^+\pi^-)}} \simeq 1 - 6\,\mathrm{Re}(\varepsilon'/\varepsilon)$$

R is called the Double Ratio

Double Ratio

$$R = \frac{\Gamma(K_L \to \pi^0\pi^0)\,\Gamma(K_S \to \pi^+\pi^-)}{\Gamma(K_S \to \pi^0\pi^0)\,\Gamma(K_L \to \pi^+\pi^-)} \simeq \frac{N(K_L \to \pi^0\pi^0)\,N(K_S \to \pi^+\pi^-)}{N(K_S \to \pi^0\pi^0)\,N(K_L \to \pi^+\pi^-)}$$

IF the 4 modes are taken

- simultaneously
- in the same decay region

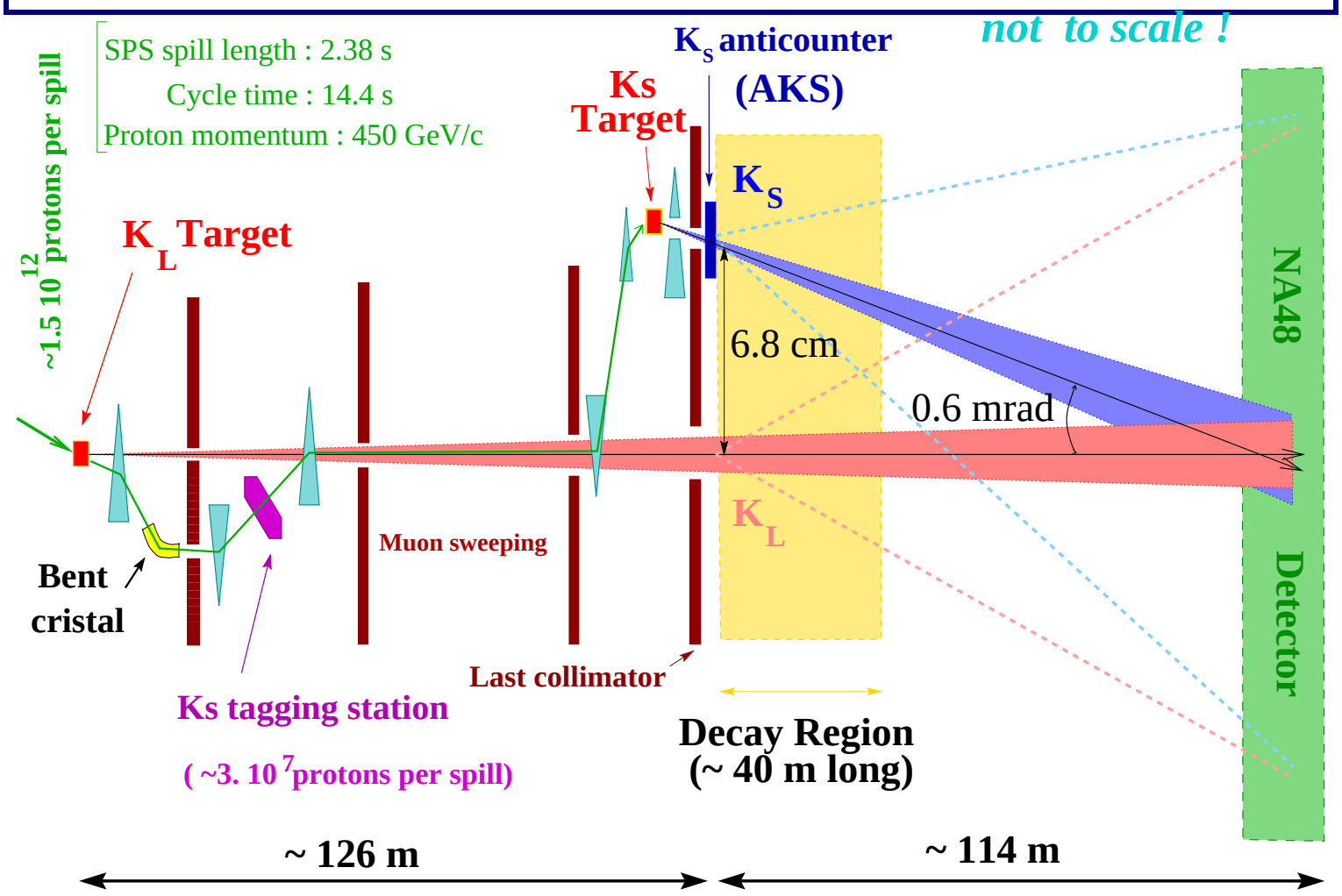
$\Rightarrow$ "just" count number of events

NA48 is a "Perturbative Expansion" experiment:

$$R = 1 - \Delta R^{(1)} + \Delta R^{(2)}$$

- $\Delta R^{(1)}$: 1st order term ($\approx 1\%$)
  $\Rightarrow$ NA48 "magic" recipe;
- $\Delta R^{(2)}$: 2nd order term ($\approx$ few‰)
  $\Rightarrow$ small corrections;

Simultaneous and collinear K_L and K_S beams

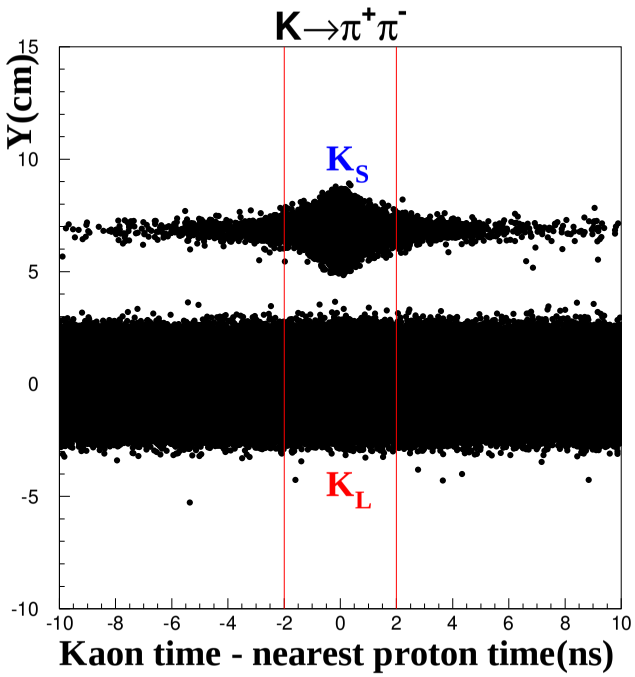


K_S/K_L variations (RMS $\approx 9\%$) $\Rightarrow$ reweight K_S's to keep K_S/K_L constant

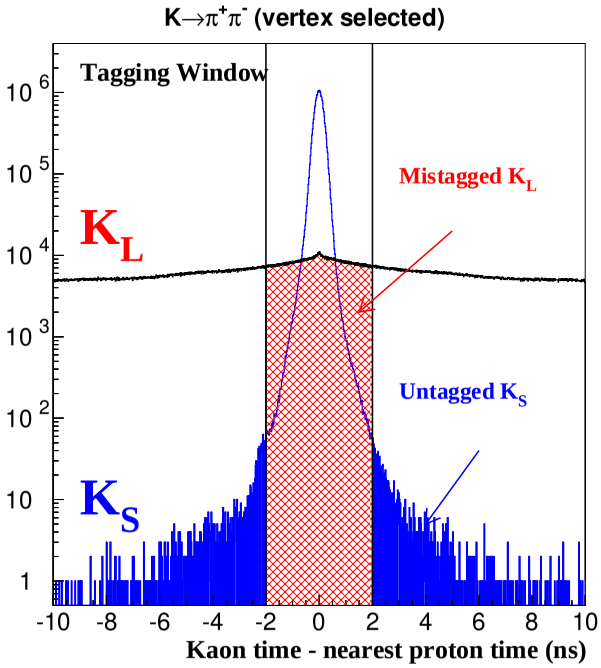
- K_S reweighting is a small effect on R ($\approx 3 \times 10^{-4}$)

K_S and K_L are distinguished by proton tagging upstream of the K_S target

Tagging



Tagging inefficiency
$P(K_S \to K_L) : \alpha_{SL}^{+-}$
$= (1.6 \pm 0.03) \times 10^{-4}$

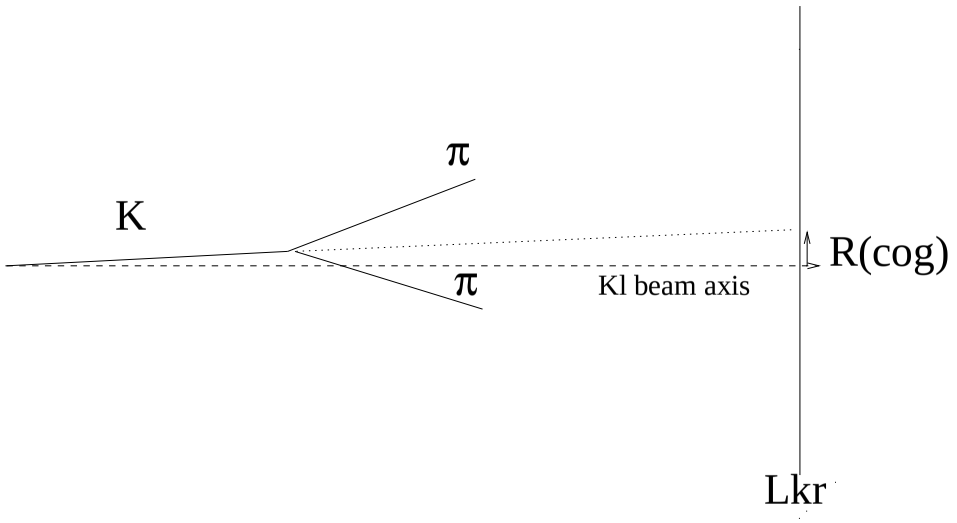


Accidental tagging
$P(K_L \to K_S) : \alpha_{LS}^{+-}$
$= (10.649 \pm 0.008)\%$

In the Double Ratio we account for the accidental tagging

Decay region definition

- $0 \leq \tau \leq 3.5$
  - τ = proper time along the beam axis, in K_S lifetime units
  - $\tau = (z_{vertex} - z_0) \frac{M_K}{E_K} \frac{1}{c\tau_{K_S}}$
  - For K_S beginning of decay region is defined by AKS anticounter:
    - Photon converter: iridium cristal 3 mm thick, 1.79 X_0 at 0 angle
    - Track veto: scintillator counter, (22 ± 0.5) mm downstream
- $70 \leq E_K \leq 170$ GeV (K_L/K_S variations$< 20\%$)
  Measure R in K energy bins (5 GeV wide)
  $\Rightarrow$ insensitive to $K_S - K_L$ energy spectrum difference
- Centre of gravity $R_{COG} \leq 10$ cm
  R_{COG} is the K impact point extrapolated to the calorimeter



Lifetime weighting principle

At the same z $\Rightarrow$ Acceptance K_S $= K_L$

But very different decay lenghts: $\tau_{K_L} \approx 600 \times \tau_{K_S}$

$\Rightarrow$ Different total acceptance for K_S and K_L

$\Rightarrow$ large correction on R

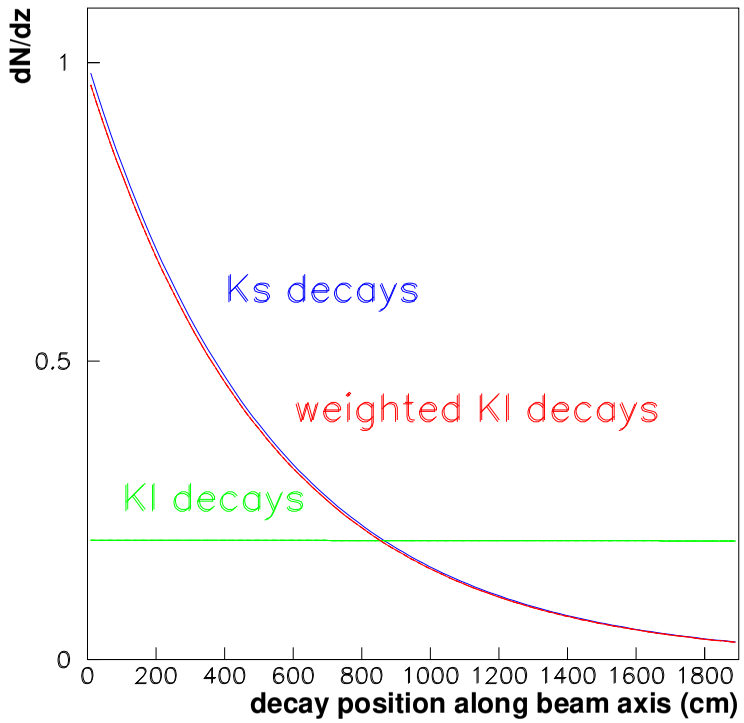
Solution: Weight K_L events with:

$$w = \frac{\pi\pi \text{ decay rate in } K_S}{\pi\pi \text{ decay rate in } K_L} \approx e^{-z/(\beta\gamma c)(1/\tau_{K_S} - 1/\tau_{K_L})}$$

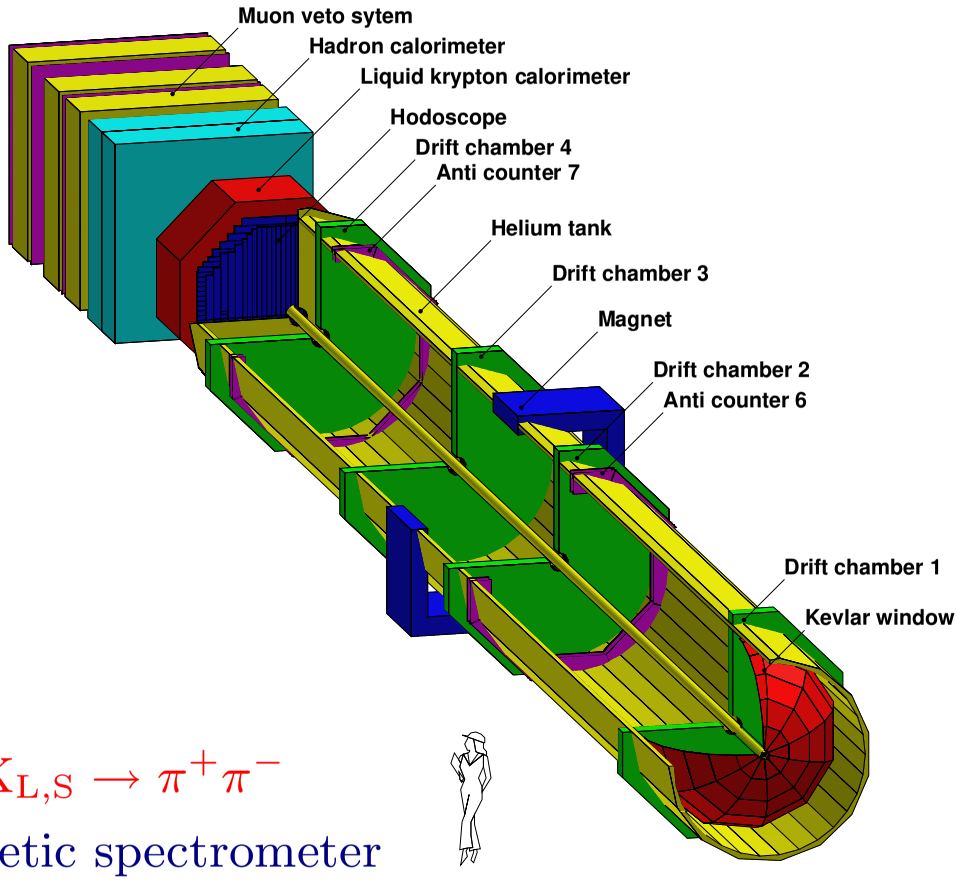
Same decay vertex distribution for K_S and weighted K_L

Acceptance correction cancels

Price: Increase in statistical error ($\approx 35\%$)



Detectors



- $K_{L,S} \to \pi^+\pi^-$

magnetic spectrometer

4 drift chambers + magnet $\to$ 265 MeV p_t kick

$$\frac{\sigma(p)}{p} \simeq 0.5\% \oplus 0.009\, p\%$$ p in GeV/c

- $K_{L,S} \to \pi^0\pi^0$

Liquid Krypton e.m. calorimeter

13212 cells: $2\times2\,\mathrm{cm}^2 \times 27\ X_0$ ($X_0 = 4.7$ cm)

$$\frac{\sigma(E)}{E} = \frac{3.2\%}{\sqrt{E}} \oplus \frac{0.09}{E} \oplus 0.42\%$$ E in GeV

Projective geometry $\Rightarrow$ 114 m upstream decay region

Dead time conditions:

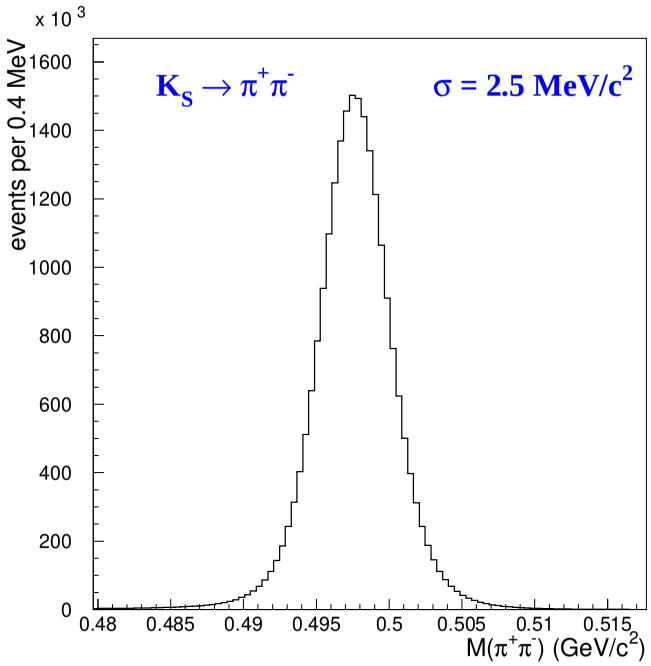
$\approx 1.5\%$ from $\pi^+\pi^-$ trigger,

$\approx 20\%$ from drift chamber multiplicity limit

$\Rightarrow$ applied offline to all events

$\pi^+\pi^-$ reconstruction

500 KHz $\Rightarrow$ 2-level trigger, $(97.896 \pm 0.024)\%$ eff. $\Rightarrow$ 2 KHz



Background rejection:

No μ-counters hits

$E/p < 0.8$

$|M_{\pi\pi} - M_K| < 3\sigma$

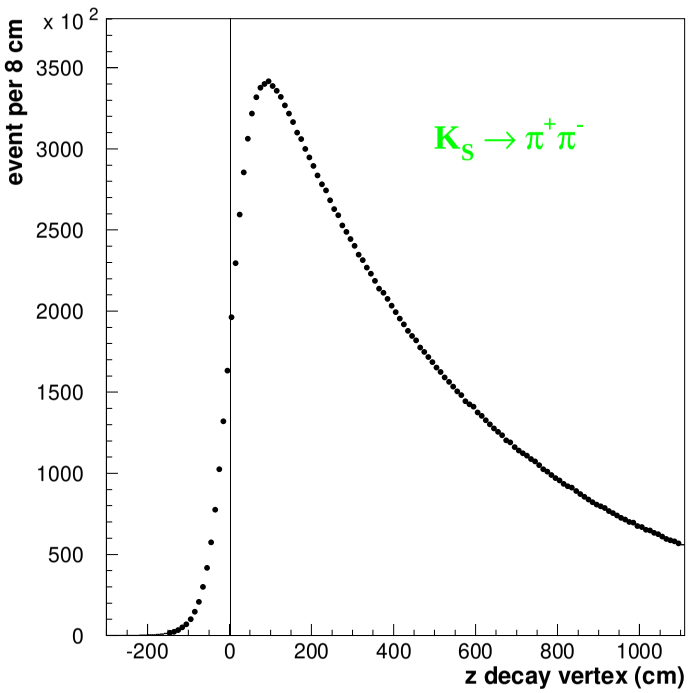
$P_T'^2 < 200$ (MeV/c)^2

$\frac{|p_1 - p_2|}{p_1 + p_2} < f(E_K)$

$\pi^+\pi^-$ energy: opening angle and tracks energy ratio

$E_K^2 = \frac{C}{\theta^2}\left\{m_K^2 - C\ m_\pi^2\right\}$; $\quad C = 2 + \frac{E_{\pi 1}}{E_{\pi 2}} + \frac{E_{\pi 1}}{E_{\pi 2}}$

$\Rightarrow$ geometry of the drift chambers



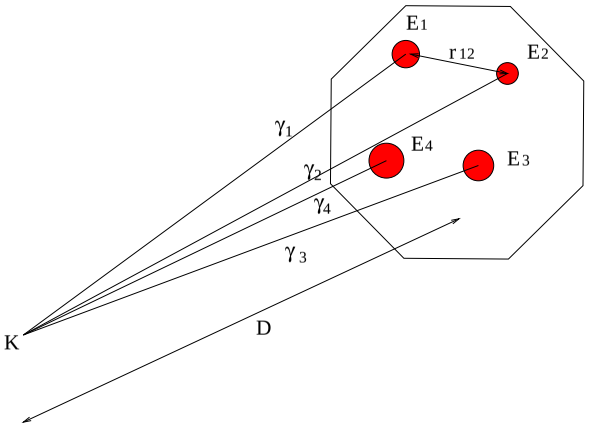
Reconstruction of AKS position: check of geometry

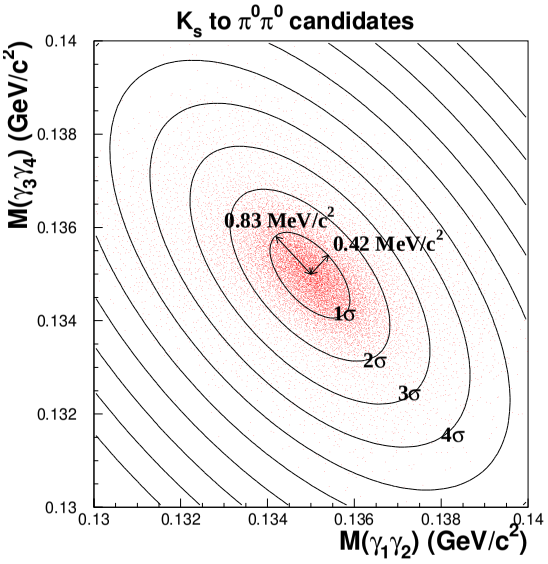
$\Rightarrow \Delta z = 2$ cm

$\pi^0\pi^0$ Reconstruction

500 KHz $\Rightarrow$ $\pi^0\pi^0$ trigger, $(99.920 \pm 0.009)\%$ eff. $\Rightarrow$ 2 KHz

$K^0 \rightarrow 2\ \pi^0 \rightarrow 4\gamma$

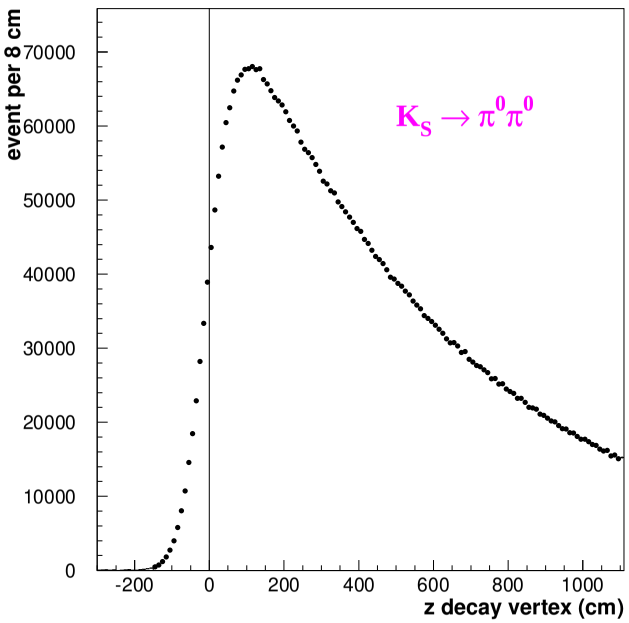




$$D = \frac{\sqrt{\sum E_i E_j \times (r_{ij})^2}}{M_K}$$

$$m_{ij} = \frac{\sqrt{E_i E_j} \cdot r_{ij}}{D}$$

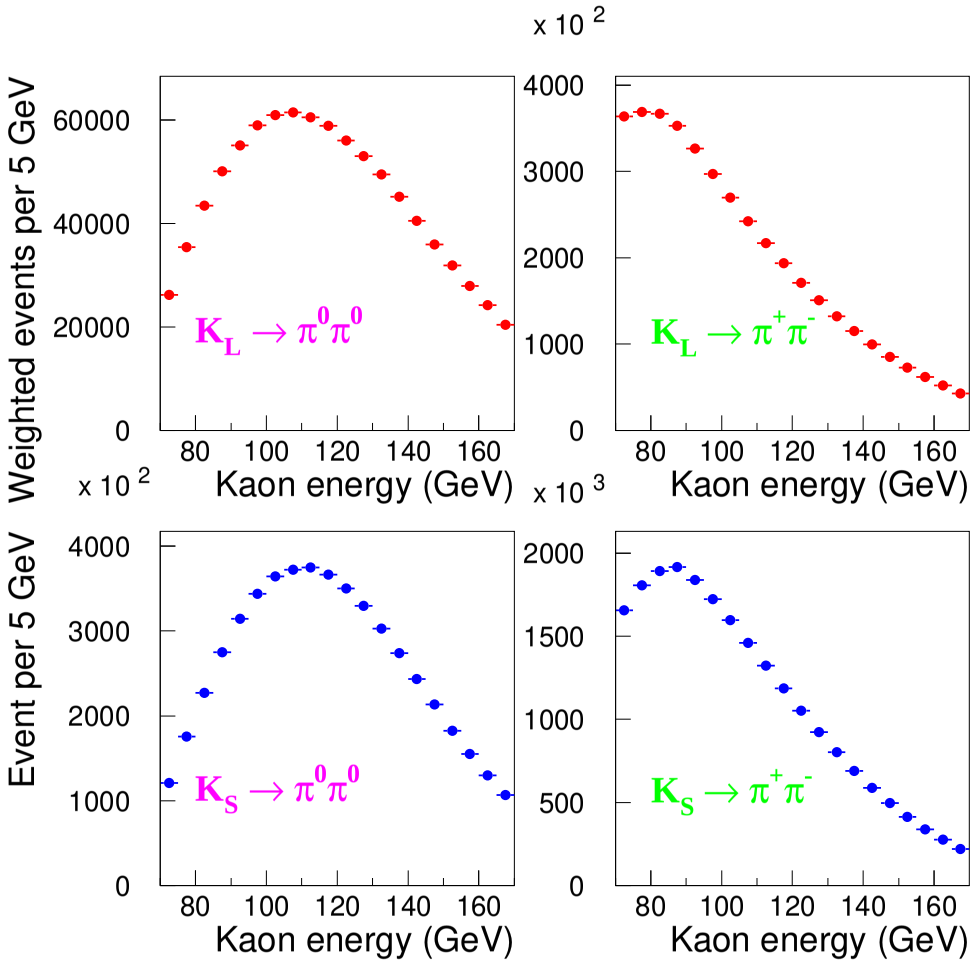
- Cut on χ^2 from π^0 masses
- Veto events with 5th cluster in time



Reconstruction of AKS position: adjust energy scale $\Rightarrow$ match the AKS nominal position

energy$\Rightarrow$geometry

First Order Result



1998+1999 Statistics:
(corrected for mistagging)

$K_L \to \pi^0\pi^0$: 3.29×10^6, $K_S \to \pi^0\pi^0$: 5.21×10^6
$K_L \to \pi^+\pi^-$:14.45×10^6, $K_S \to \pi^+\pi^-$:22.22×10^6

$$R = 1 - (1.261 \pm 0.101)\% + \Delta R^{(2)}$$

Second Order Result

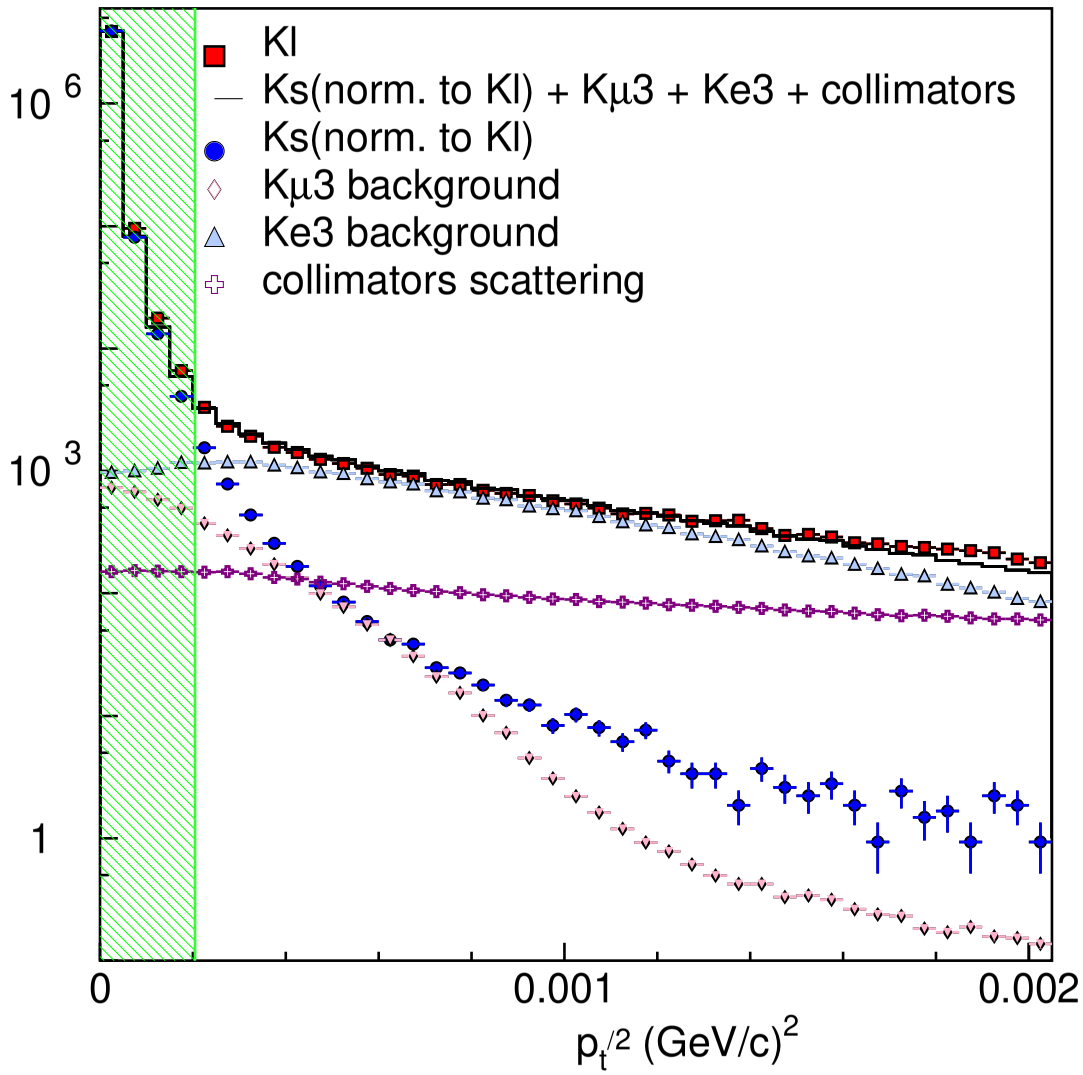
Corrections to the first order result

- Charged Background
- Neutral Background
- Beam Scattering Background
- Tagging (Neutral-Charged difference)
- Triggers inefficiency
- AKS veto inefficiency
- Energy scale uncertainty
- Acceptance
- Accidental activity induced losses

$\pi^+\pi^-$ background subtraction

The residual K_L background is estimated:

- using control region in $M_{\pi\pi}$ and $P_T'^2$;
- using sample of identified $Ke3$ and $K\mu3$ decays



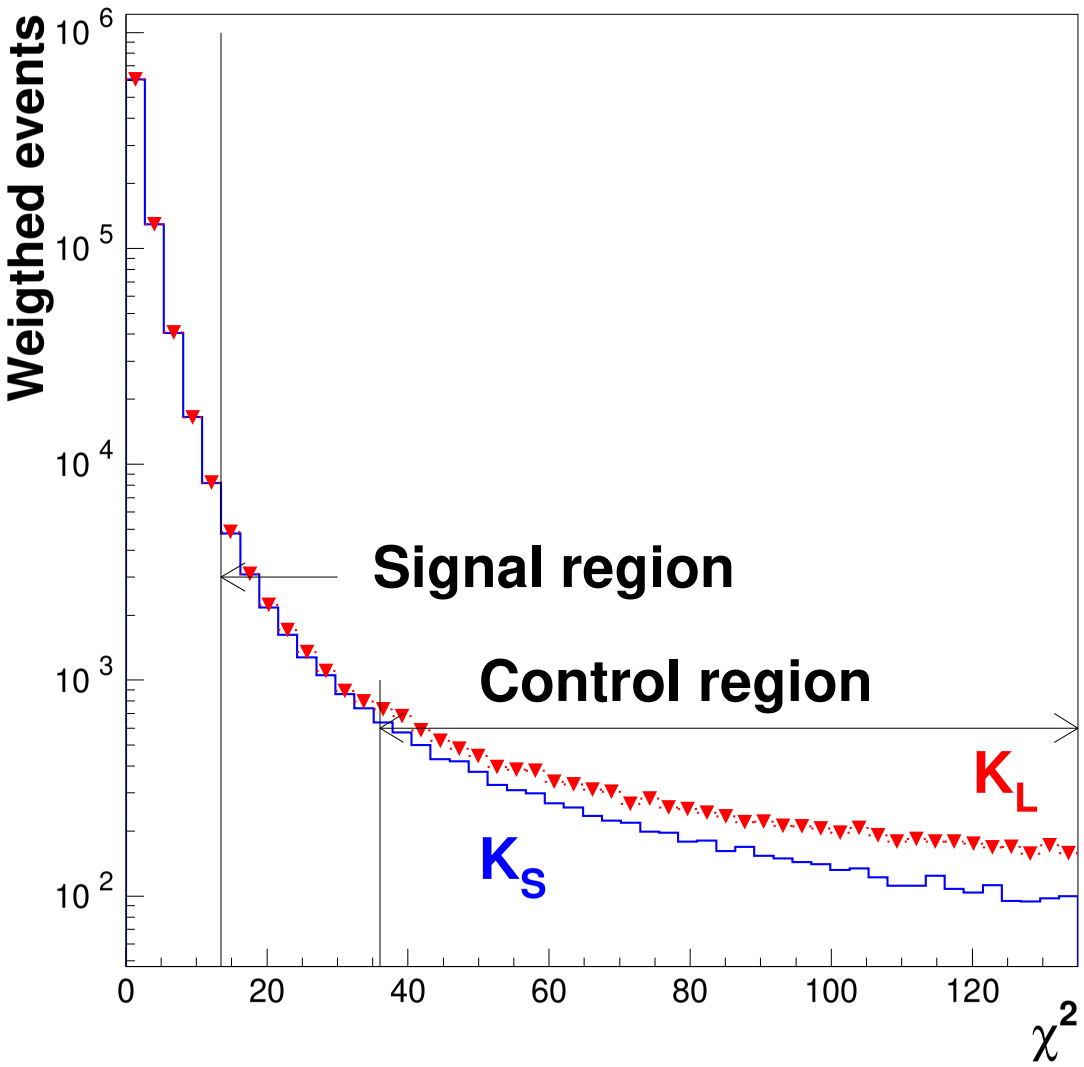
Background $= (16.9 \pm 3.0) \times 10^{-4}$

(systematic error: variation of control regions, modelling of $P_T'^2$ shape)

$\pi^0\pi^0$ background subtraction

The residual K_L background is estimated:

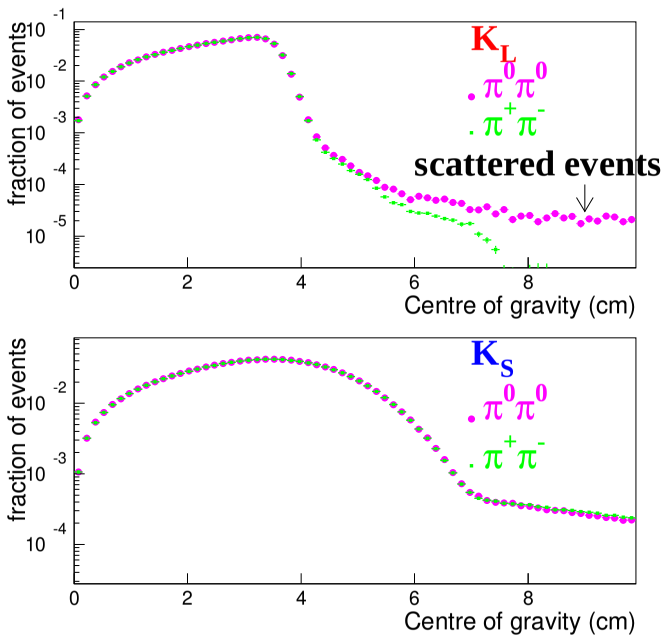
- using control region in χ^2
  ($3\pi^0$ background is almost flat)
- using K_S events to evaluate resolution tails



Background $= (5.9 \pm 2.0) \times 10^{-4}$

(systematic error: uncertainty in background extrapolation from MC)

Beam Scattering Background



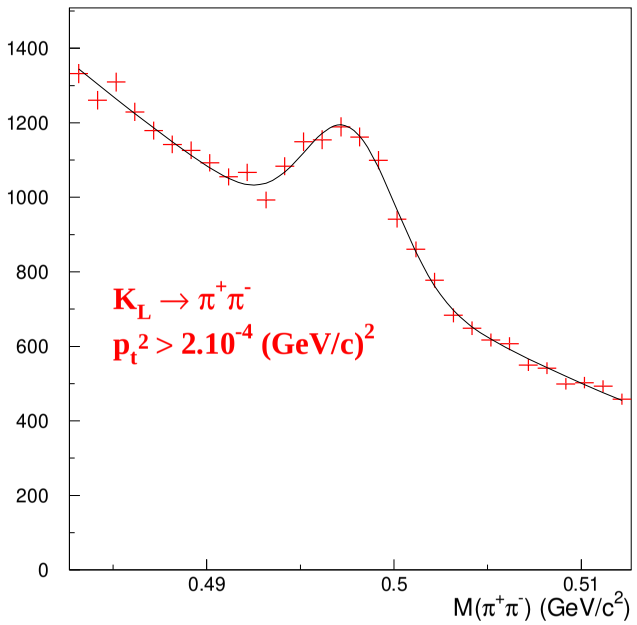
K_L beam scattering in final collimator:
removed in $\pi^+\pi^-$ sample by $P_T'^2$ cut
kept in $\pi^0\pi^0$ sample
$\Rightarrow$ correction on R

K_S beam scattering removed by COG cut
$\Rightarrow$ $\pi^+\pi^-$ and $\pi^0\pi^0$ symmetric
$\Rightarrow$ no effect on R

The collimator background is estimated:

$\pi^+\pi^-$ events with $P_T'^2 > 200(MeV/c)^2$ with $M_{\pi\pi} = M_K$

cross-check in $\pi^0\pi^0$ R_{COG} distribution



Background in $\pi^0\pi^0 = (9.6 \pm 2.0) \times 10^{-4}$

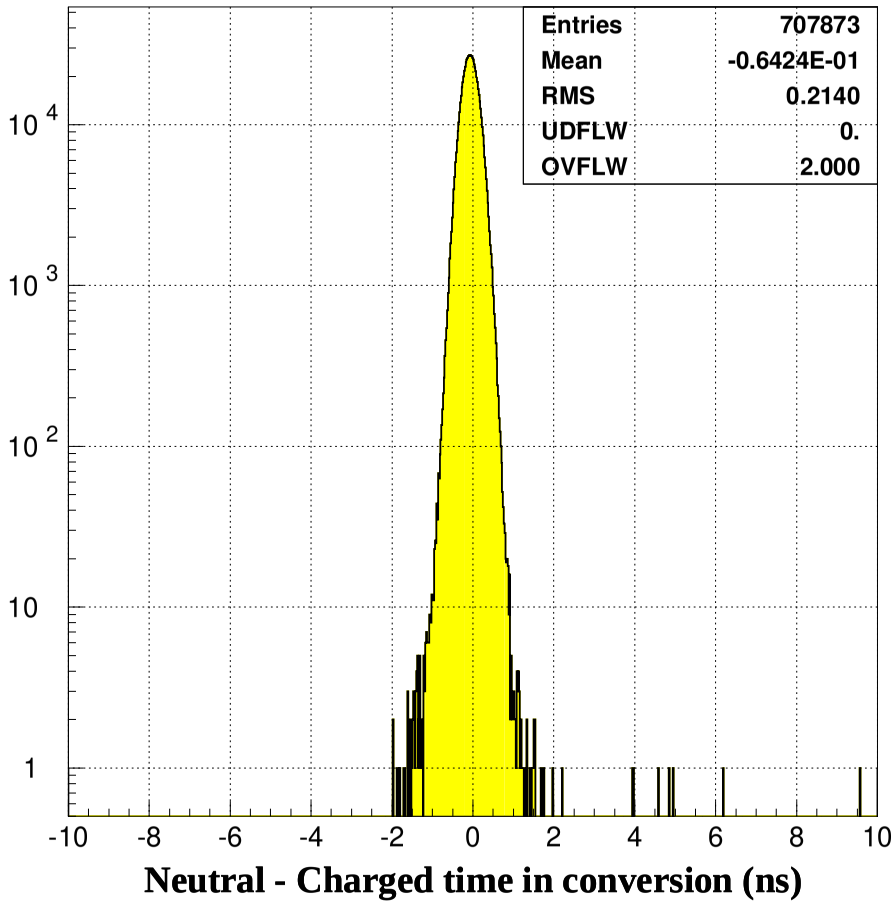
Tagging Inefficiency

$P(K_S \rightarrow K_L) : \alpha_{SL}^{+-} = (1.6 \pm 0.03) \times 10^{-4}$

α_{SL}^{+-} dominated by tagger inefficiency
($\pi^+\pi^-$ and $\pi^0\pi^0$ symmetric)

$\Delta\alpha_{SL} = \alpha_{SL}^{00} - \alpha_{SL}^{+-} \Rightarrow$ Difference in tails between $\pi^+\pi^-$ and $\pi^0\pi^0$ event time measurements

$\Rightarrow$ Compare directly charged and neutral measurements using events with γ's and e^+e^-

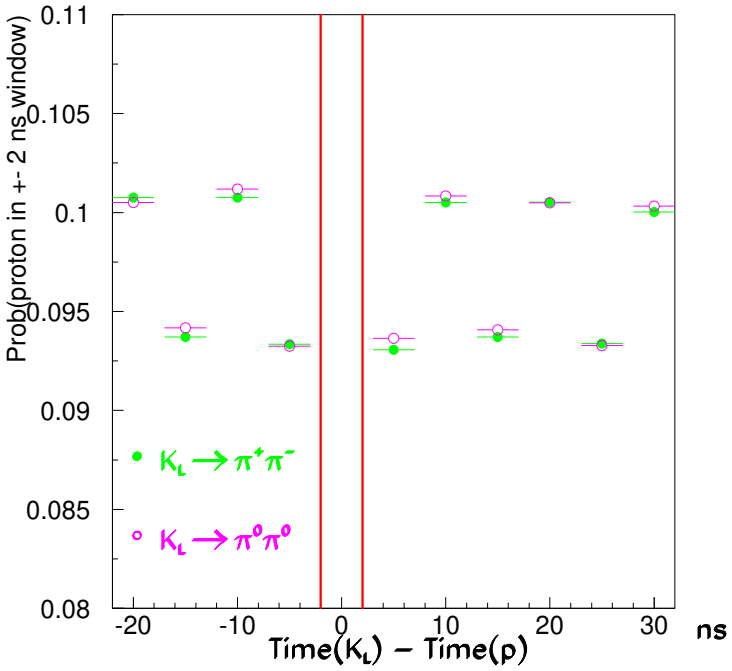


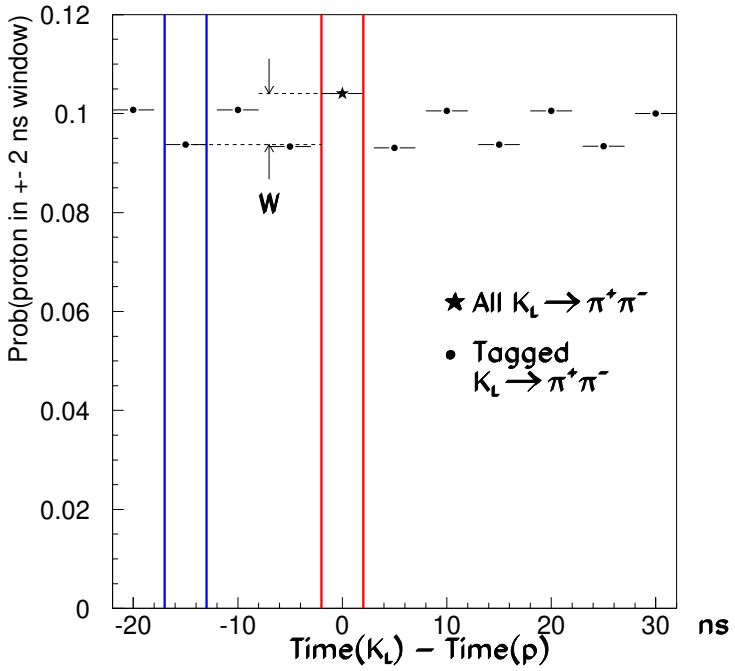
$$\Delta\alpha_{SL} = (0 \pm 0.5) \times 10^{-4}$$

$$\boxed{\Delta R = (0 \pm 3.0) \times 10^{-4}}$$

Accidental Tagging

$$P(K_L \rightarrow K_S) : \alpha_{LS}^{+-} = (10.649 \pm 0.008)\%$$





Sidebands of tagger selected K_L

$\Delta\alpha_{LS}^{sidebands} = (3.0 \pm 1.0) \times 10^{-4}$

Central window extrapolation: W

$\pi^+\pi^-$: vertex selected K_L

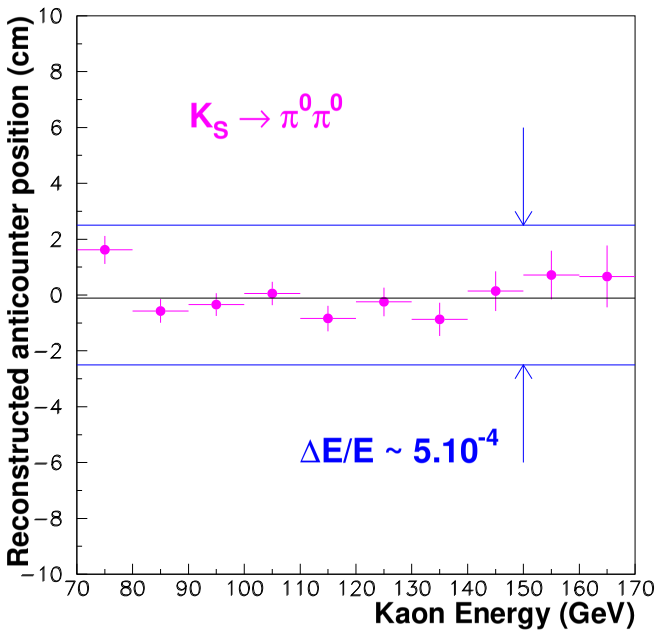
$\pi^0\pi^0$: $3\pi^0$ events (only K_L)

$\Delta W = (1.3 \pm 1.1) \times 10^{-4}$

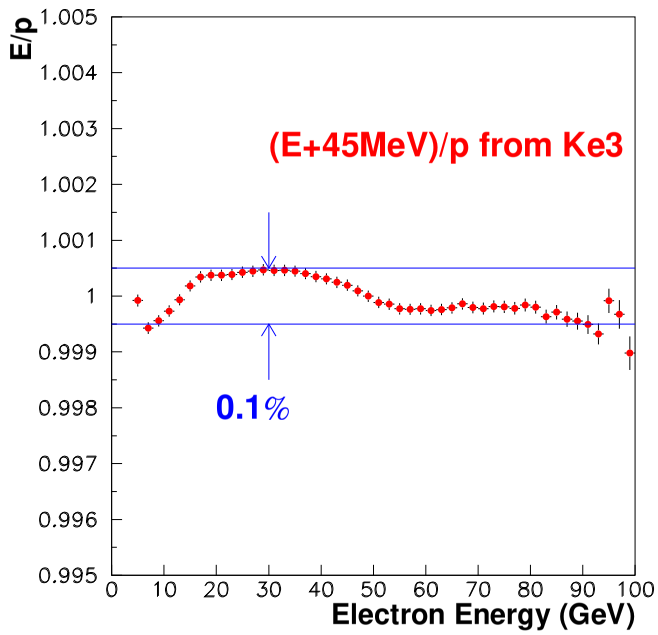
$\Delta\alpha_{LS} = (4.3 \pm 1.8) \times 10^{-4}$

$\Delta R = (8.3 \pm 3.4) \times 10^{-4}$

Energy scale checks

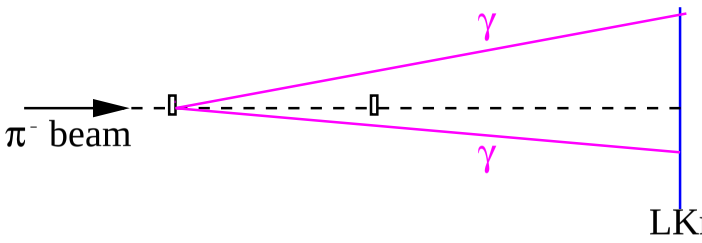


$\pi^0\pi^0$: energy scale independent of K energy (non linearity check)



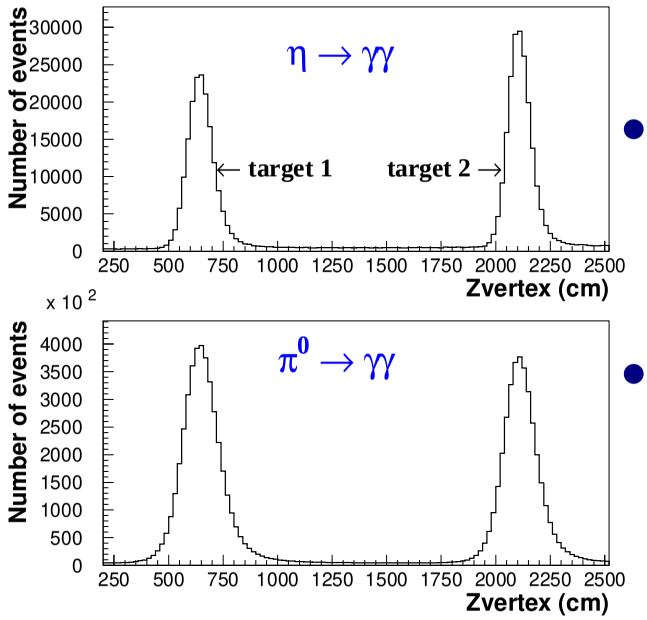
Electrons from Ke3 decays E/p constant within $\approx 0.1\%$ between a few GeV and 100 GeV

Energy scale checks, contd.



Special run π^- beam directed to two thin targets

- Produce π^0 and η with known decay position



- Use $\gamma\gamma$ decays to reconstruct vertex (assuming π^0 or η masses)
- Using $\eta \to 3\pi^0 \to 6\gamma$ $\Rightarrow$ measure M_η / M_{π^0}

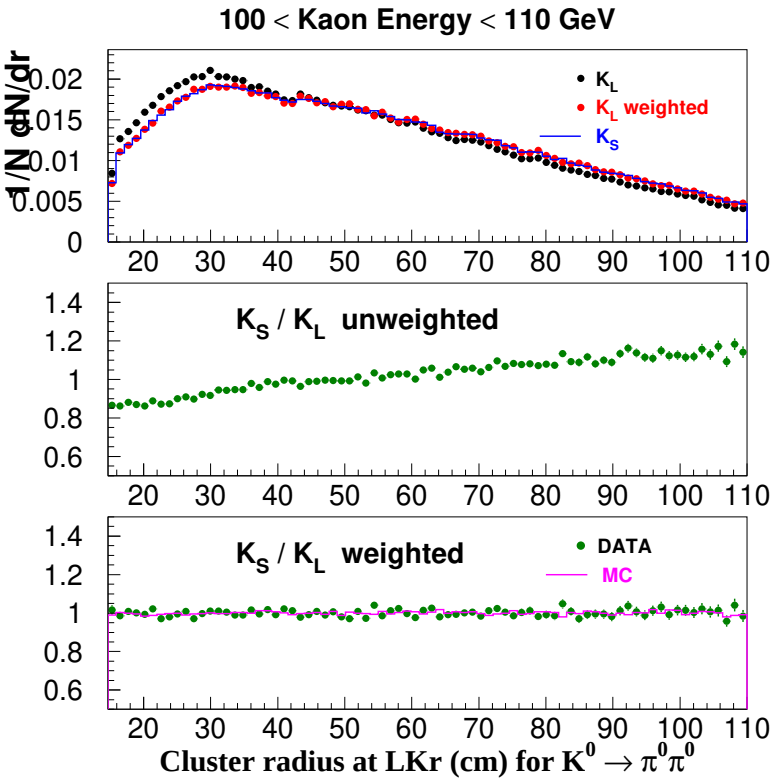
NEW Preliminary result:
$M_\eta = (547.823 \pm 0.020_{stat} \pm 0.055_{syst})$ MeV

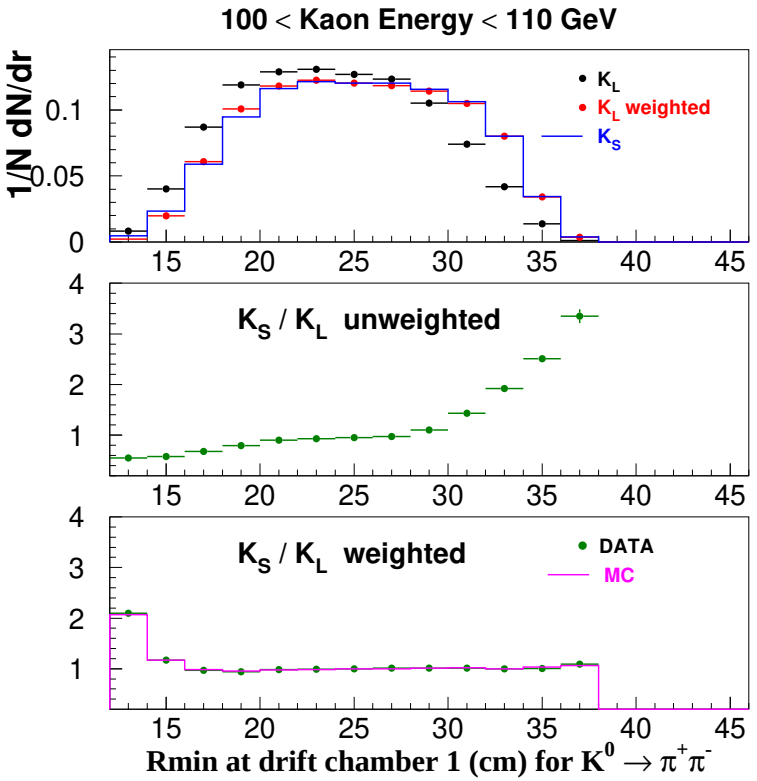
Total uncertainties on neutral energy scale

$$\Delta R = \pm 5.8 \times 10^{-4}$$

Acceptance Correction

K_L lifetime weighting $\Rightarrow$ minimize $K_L - K_S$ detector illumination difference and acceptance correction





Small residual effect from 0.6 mrad angle between K_L and K_S beams

$$\Delta R = (26.7 \pm 4.1_{\mathrm{MCstat}} \pm 4.0_{\mathrm{syst}}) \times 10^{-4}$$

Accidental activity

Accidental activity from beam $\Rightarrow$ Event losses
Cancel at first order in R

Residual effect:

$\Delta R \approx \Delta(\pi^+\pi^- - \pi^0\pi^0) \times \Delta(K_L - K_S)$

- $\Delta(\pi^+\pi^- - \pi^0\pi^0)$: difference between neutral and charged losses;
  minimized by applying dead time conditions to all modes: $(1.4 \pm 0.7)\%$
- $\Delta(K_L - K_S)$: difference in accidental activity seen by K_L and K_S;
  small by design of the experiment:
  - Simultaneous beams $\Rightarrow$ K_L and K_S events see the same activity, within 1% (checked directly in data)
  - Lifetime weighting $\Rightarrow$ K_L and K_S events illuminate the same parts of the detector

Uncertainty on R:

- Intensity difference $\Rightarrow \Delta R = (0 \pm 3) \times 10^{-4}$
- Residual illumination difference
  $\Rightarrow \Delta R = (0 \pm 3) \times 10^{-4}$ (studied using random event overlays to $\pi\pi$ MC and data)

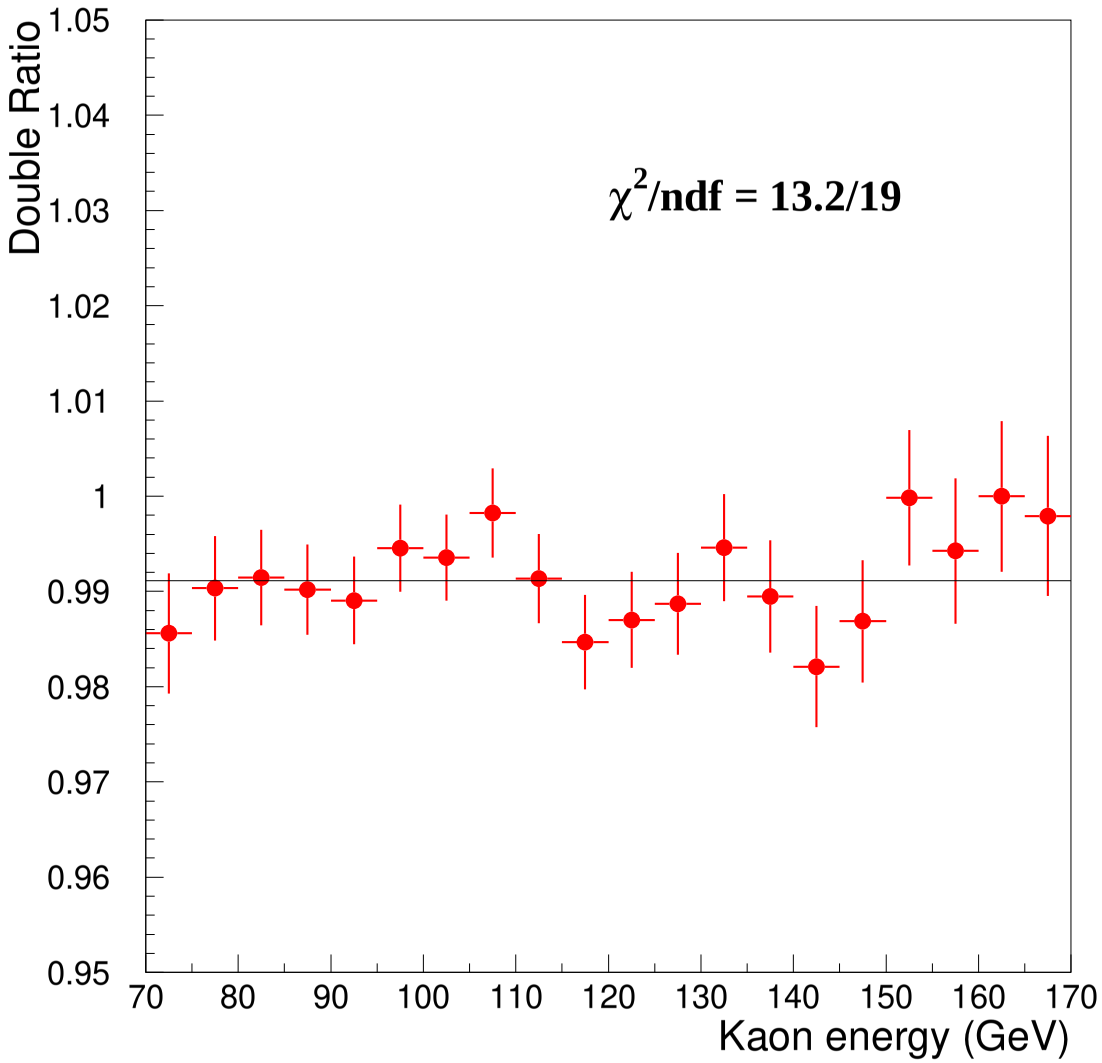
$$\boxed{\Delta R = \pm 4.4 \times 10^{-4}}$$

Second Order Corrections

Corrections and systematic uncertainties on R (Units = 10^{-4})		
$\pi^+\pi^-$ background	16.9	$\pm$ 3.0
$\pi^0\pi^0$ background	-5.9	$\pm$ 2.0
beam scattering	-9.6	$\pm$ 2.0
Tagging inefficiency		$\pm$ 3.0
Accidental tagging	8.3	$\pm$ 3.4 (part. stat)
$\pi^+\pi^-$ scale	2.0	$\pm$ 2.8
$\pi^0\pi^0$ scale		$\pm$ 5.8
AKS inefficiency	1.1	$\pm$ 0.4
Acceptance correction	26.7	$\pm$ 4.1 (MC stat)
		$\pm$ 4.0 (syst)
$\pi^+\pi^-$ trigger	-3.6	$\pm$ 5.2 (stat)
Accidental event losses		$\pm$ 4.4 (part. stat)
Total	+35.9	$\pm$ 12.6

$$R = 1 - (1.261 \pm 0.101)\% + (3.59 \pm 1.26)‰$$

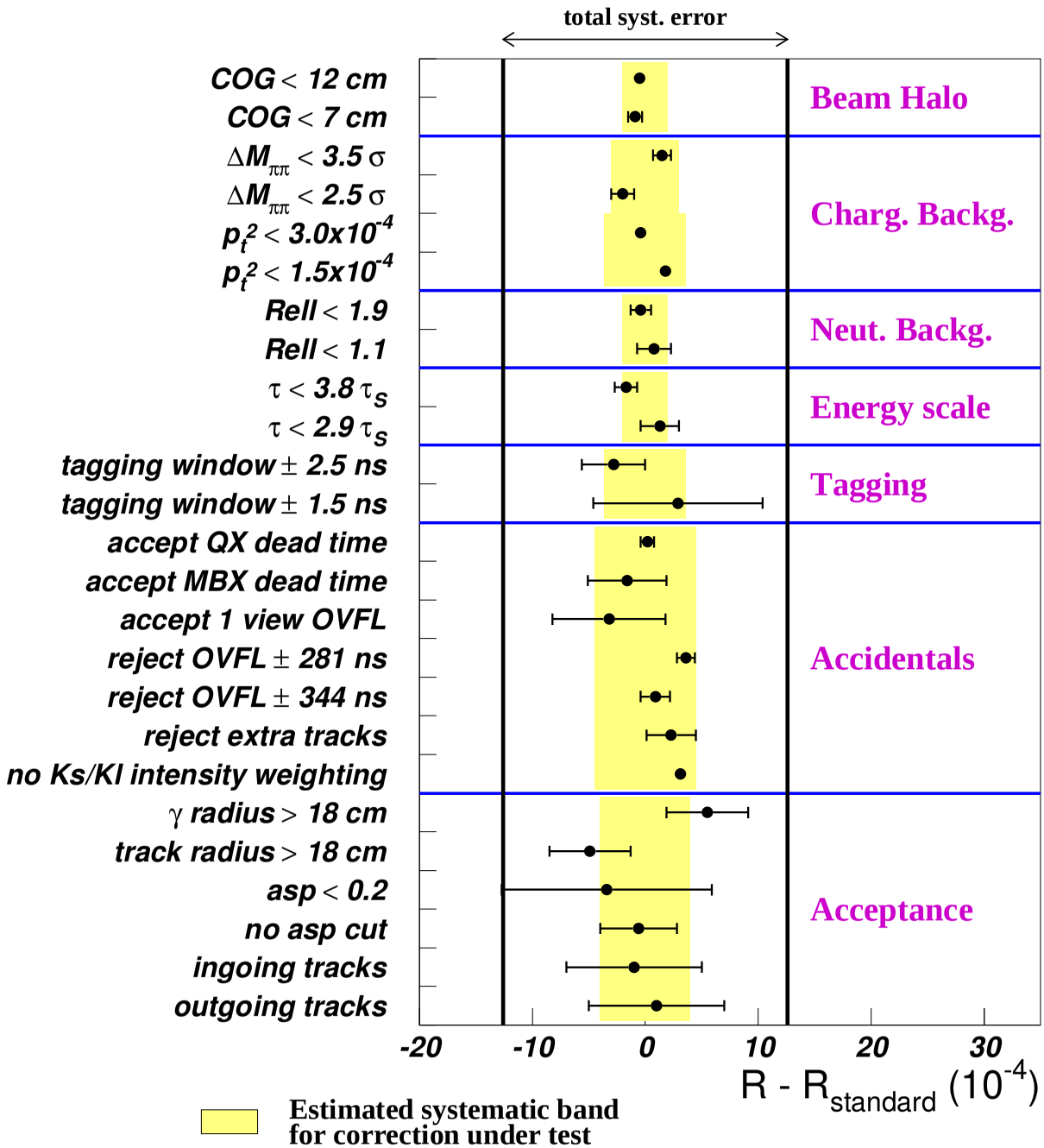
The Double Ratio



$$\mathrm{R} = 0.99098 \pm 0.00101_{stat} \pm 0.00126_{syst}$$

Checks

R stability against cut variations



Final Result

From $98 + 99$ data:

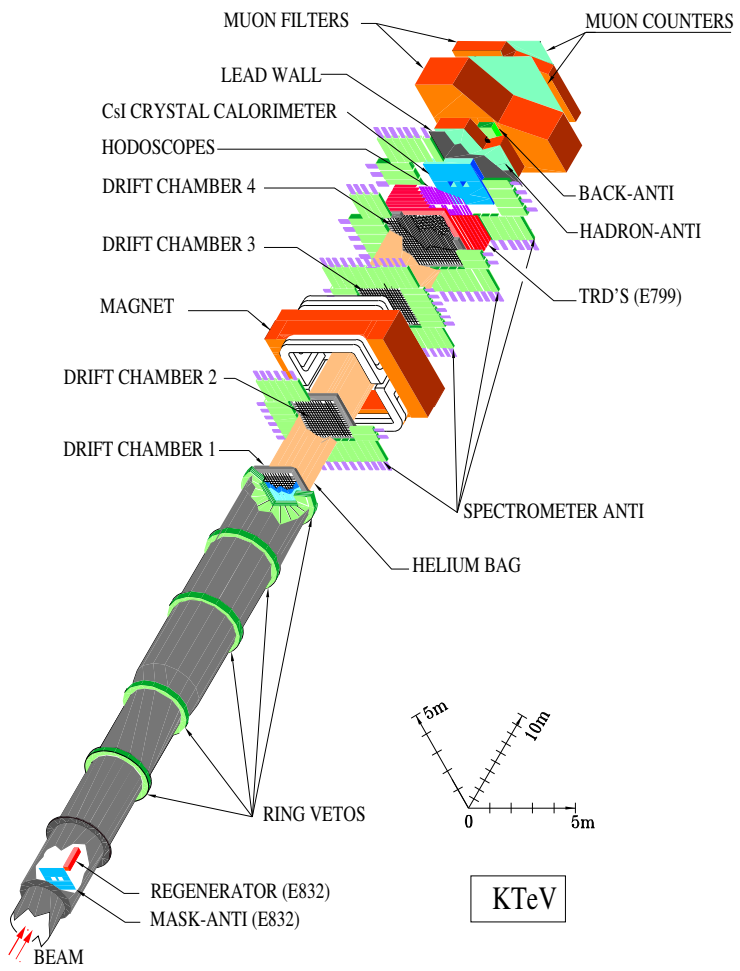
$$\mathrm{Re}(\varepsilon'/\varepsilon) = (15.0 \pm 2.7) \times 10^{-4}$$

Combining with 97 result
$(18.5 \pm 7.3) \times 10^{-4}$

$$\boxed{\mathrm{Re}(\varepsilon'/\varepsilon) = (15.3 \pm 2.6) \times 10^{-4}}$$

(5.9σ away from 0)

KTeV Experiment



"Vacuum" beam $\Rightarrow$ K_L

"Regenerator" beam $\Rightarrow$ $K_L + \rho K_S$

Charged detection: DCHs+magnet

Neutral detection: CsI crystals

Regenerator/Vacuum beam identification $\Rightarrow$ x-vertex position

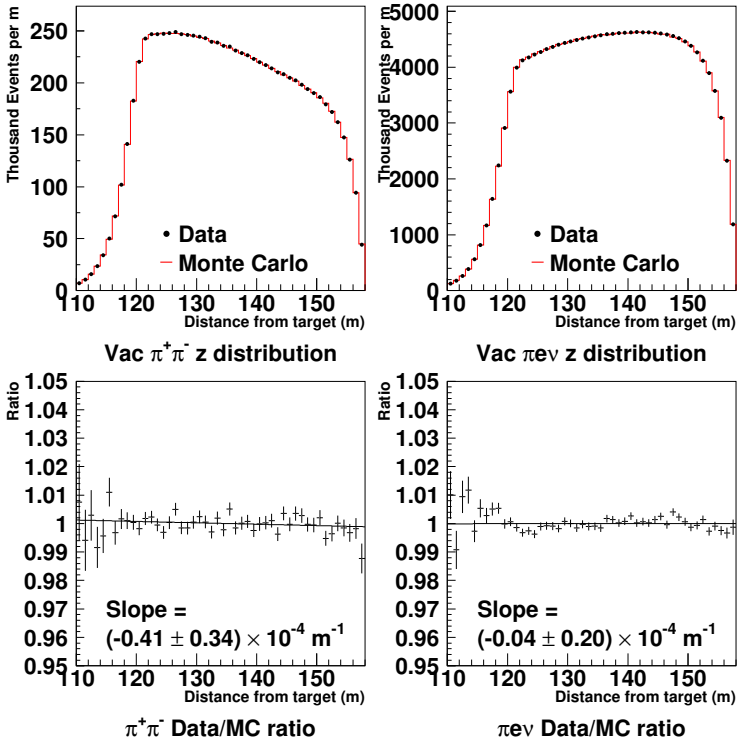
Backgrounds ($\times 10^{-3}$)

Beam	Vac.	Reg.
Charged Kl3	0.90	0.03
Ch. Coll. Scatter.	0.10	0.10
Ch. Reg. Scatter.	-	0.73
Total Charged	1.00	0.87
$3\pi^0$	1.1	0.3
Ne. Coll. Scatter.	1.2	0.9
Ne. Reg. Scatter.	2.5	11.3
Reg Hadronic Int.	-	0.1
Total Neutral	4.8	12.4

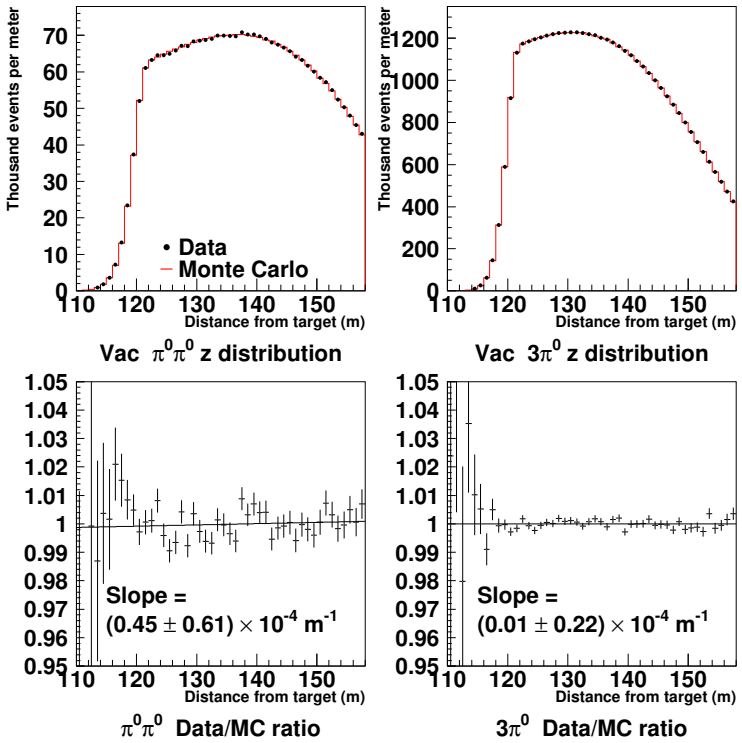
KTeV Acceptance

Detailed MC prediction $\Rightarrow$ $\approx 5\%$ acceptance correction to R
(mostly due just to simple geometry)

1997 $K \to \pi^+\pi^-$ & K_{e3}



1997 $K \to \pi^0\pi^0$ & $K_L \to 3\pi^0$

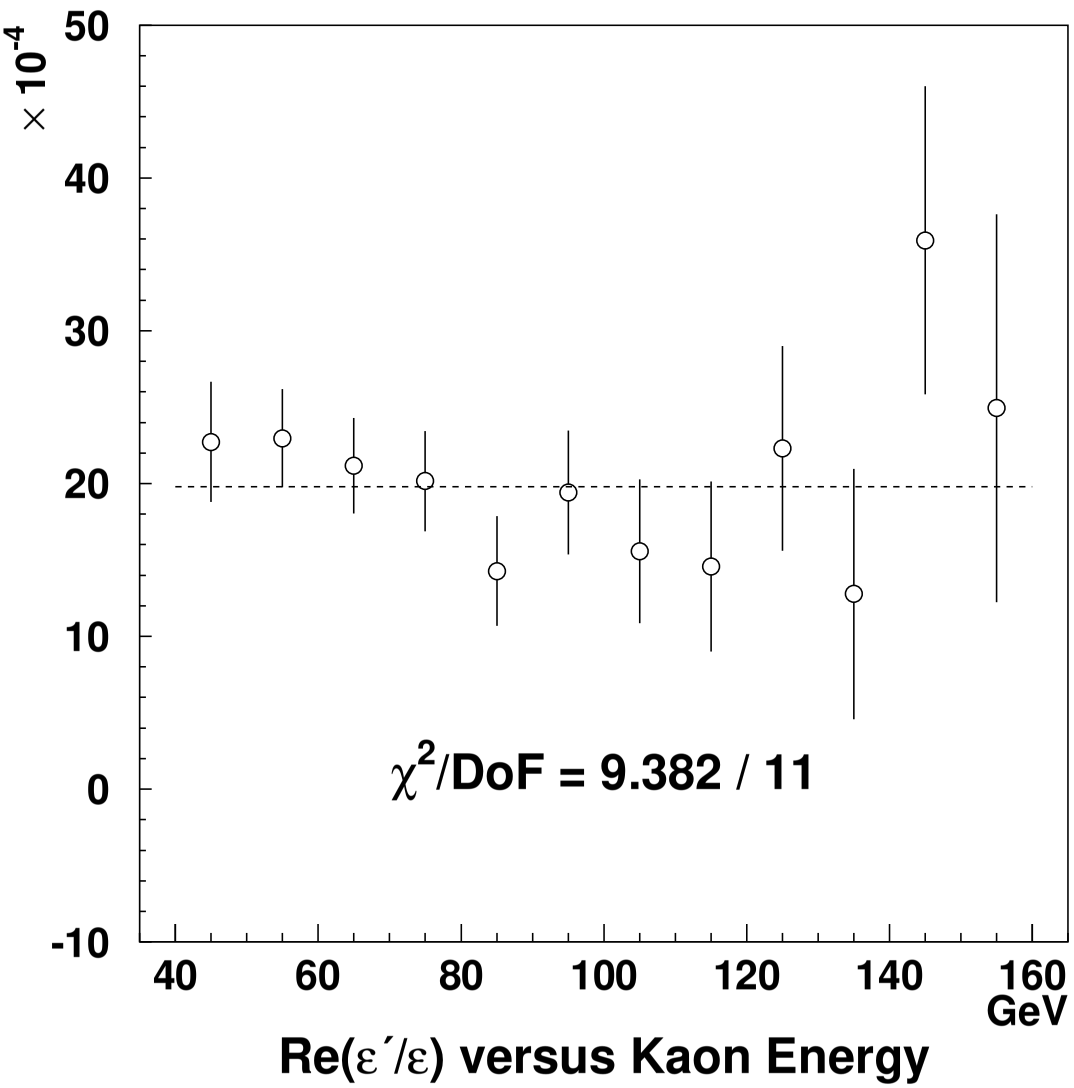


Cross-check: lifetime weighting $\Rightarrow \Delta R = -9 \pm 13_{(stat)} \pm 18_{(syst)} \times 10^{-4}$

KTeV result from 1997 data

Result from
data statistically independent of PRL published result

$$\mathrm{Re}(\varepsilon'/\varepsilon) = (19.8 \pm 1.7_{stat} \pm 2.3_{syst} \pm 0.6_{MC}) \times 10^{-4}$$



KTeV result

The published result (based on 1996 data) has been reanalyzed:

$$\mathrm{Re}(\varepsilon'/\varepsilon) = (23.2 \pm 3.0_{(stat)} \pm 3.2_{(syst)} \pm 0.7_{(MCstat)}) \times 10^{-4}$$

Combined result for the 1996-1997 dataset:

$$\mathrm{Re}(\varepsilon'/\varepsilon) = (20.7 \pm 1.5_{(stat)} \pm 2.4_{(syst)} \pm 0.5_{(MCstat)}) \times 10^{-4}$$

$$\boxed{\mathrm{Re}(\varepsilon'/\varepsilon) = (20.7 \pm 2.8) \times 10^{-4}}$$

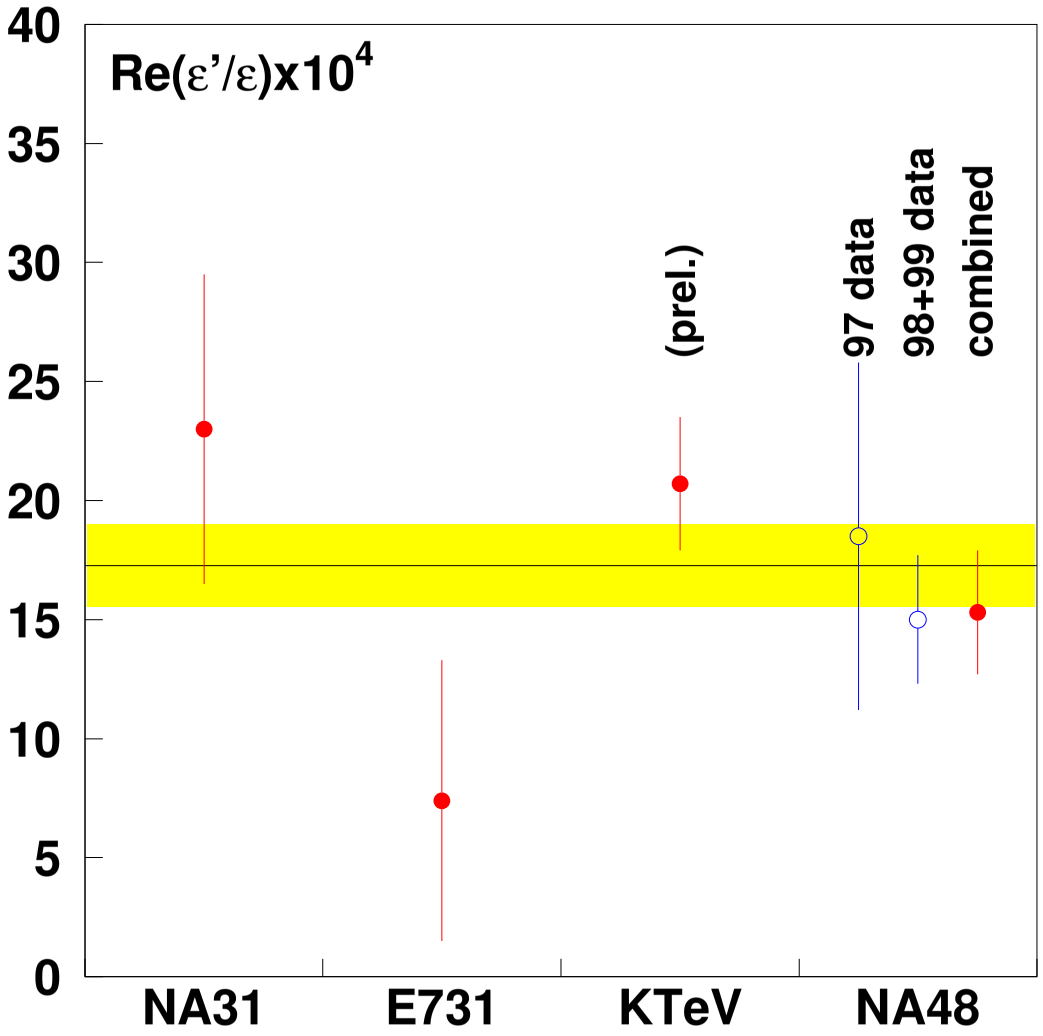
1996+1997 Statistics:

$\mathrm{K_L} \to \pi^0\pi^0$: 3.4×10^6, $\mathrm{K_S} \to \pi^0\pi^0$: 5.6×10^6

$\mathrm{K_L} \to \pi^+\pi^-$:$11.2\times10^6$, $\mathrm{K_S} \to \pi^+\pi^-$:$19.4\times10^6$

Experimental results comparison

- NA31: $(23.0 \pm 6.5) \times 10^{-4}$
- E731: $(\ 7.4 \pm 5.9) \times 10^{-4}$



World average: $\mathrm{Re}(\varepsilon'/\varepsilon) = (17.2 \pm 1.8) \times 10^{-4}$
with $\chi^2/\mathrm{ndf} = 5.5/3$ (14% probability)
$\Rightarrow$ Error scaling: $\pm 1.8 \times 10^{-4} \Rightarrow \pm 2.4 \times 10^{-4}$

Theoretical predictions: $(-1 \Leftrightarrow +4) \times 10^{-3}$

Perspectives for $\mathrm{Re}(\varepsilon'/\varepsilon)$ and Conclusions

- NA48: july-october 2001 $\Rightarrow$ new ε'/ε run:
  - Different beam conditions (spill):
    97-99: 2.4 s every 14.4 s ($E_p = 450$ GeV)
    2001: 5.2 s every 16.8 s ($E_p = 400$ GeV)
    $\Rightarrow$ better duty cycle
  - Expect $> 1.5 \times 10^6$ $\mathrm{K_L} \to \pi^0\pi^0$
    at lower instantaneous intensity
  - complete statistics and verify result under different conditions
- KTeV: analysis of 1999 data (same statistics as 1996+1997)

New NA48 result from 3 years of data taking

$$\boxed{\mathrm{Re}(\varepsilon'/\varepsilon) = (15.3 \pm 2.6) \times 10^{-4}}$$

My personal world average:

$$\mathrm{Re}(\varepsilon'/\varepsilon) = (17.2 \pm 2.4) \times 10^{-4}$$